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Review

Modelling Approaches of Life Cycle Cost–Benefit Analysis of Road Infrastructure: A Critical Review and Future Directions

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Abstract: Cost–benefit analysis (CBA) is considered an effective evaluation method for fostering optimal decision making and ranking of road infrastructures over decades. This paper introduces a comprehensive systematic literature review focusing on CBA's methodological perspective for identifying its current modelling approaches and scrutinizing their key features and encompassed tools. Fifty-six relevant studies were extracted from Web of Science, Scopus and Google Scholar from 2005 until 2020. Initially, the bibliometric analysis presents an overall illustration of the most significant CBA concepts. The descriptive statistics determined eight distinct modelling categories used for CBA implementation, each encompassing three different modelling approaches for capturing the data risk assessment (deterministic or probabilistic), CBA's parameters interactive behavior (static or dynamic) and the considered economies (microeconomic or macroeconomic). In-depth content analysis led to the interpretation of the current status of extant models and the identification of three main knowledge gaps: the absence of the CBA's inputs updating into a probabilistic environment, the deficiency of a dynamic interdependent framework and the necessity of homogenous cost datasets for road projects. Future research directions and a conceptual framework for modelling CBA into a microeconomic, probabilistic and dynamic environment are proposed providing decision-makers with new avenues for more reliable CBA modelling.

Keywords: cost–benefit analysis; life-cycle cost; road infrastructure projects; modelling approaches; dynamic framework; Bayesian analysis; conceptual model; project evaluation

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1. Introduction

The Road infrastructure projects (RIPs) underpin countries' economic, social and numerous other important aspects of lifecycle development [1,2]. Decision-making in road infrastructure planning relies extensively on various impact assessment methods, with the cost–benefit analysis (CBA) being the most common contemporary appraisal method [3,4]. CBA has been an essential tool over several decades, particularly for evaluating, ranking [5] and identifying the transport investment with the best cost–efficiency to provide transportation planners and decision makers with more objective and unquestionable choices [6].

In contrast to the extensive extant literature on various forms of CBA studies, only two literature review papers were found concerning CBA in the road transport field, examining the issue in different contexts. Beria et al. [7] reviewed the role assigned to CBA assessment in the infrastructure planning systems of six European countries and made comparisons among the different procedures applied in each country. Donais et al. [4] reviewed 66 papers between 2000–2018 regarding the CBA and multicriteria decision analysis (MCDA) methods in terms of the possible ways to combine them, their capability for covering sustainability in transport and strengths and weaknesses.

Apparently, a review of modelling approaches regarding CBA's implementation was out of the scope of previous studies. However, a key aspect of CBA is the currently used methods for conducting economic evaluation since their accuracy is crucial for cost allocation and choosing among several investments' alternatives in the decision-making process.

Therefore, this study attempts to go beyond the already studied areas of CBA and to offer evidence regarding its modelling approaches. Through a thorough systematic literature review (SLR) of the extant CBA modelling approaches for RIPs, the authors conducted a comparative and critical analysis highlighting the main research gaps. Finally, future research directions concerning probabilistic, dynamic and microeconomic approaches are proposed within a proper conceptual framework for guaranteeing validity and robustness of CBA's outcomes.

2. Systematic Literature Review: Research Protocol and Analysis

Literature reviews play an indispensable role in academic research in collecting and consolidating existing information of a specific knowledge field so as to examine the extant literature's status and identify gaps for future investigation [8]. Particularly, the SLR implements a scientific, structured and transparent process through extensive literature searches based on predetermined criteria [9], which are reproducible due to their validity, providing guarantees for the applied procedures, observations and conclusions. In the present study, the protocols used for literature searches and assessments of information derived from PRISMA guidelines [10,11] as well as [8,12,13]. The flowchart of the research protocol can be seen in Figure 1, and it is analysed in more detail subsequently.

Primarily, for the holistic investigation of the current status of CBA's method of RIPs to be guaranteed, the authors attempted to clarify the well-defined research questions of Figure 1 (step 1: "Research field and tools definition"). The peer-reviewed articles searching was performed by the Web of Science (WoS) Core Collection and Scopus bibliographic databases, which are two of the most widely accepted and well-recognized databases for high-quality bibliometric analysis (BA) [14]. The three-level structure of keywords and Boolean operators used for data mining among the fields of titles, abstracts and authors keywords into the WoS and Scopus are presented in Table A1 (in Appendix A). The scope was restricted to the English language, including the document types of journal articles and conference proceedings within a timespan between 2005–2020 because it was considered capable of capturing the dynamic evolution of the concepts that influence and develop the research topic's evolution. The primary exclusion criteria of Figure 1 were applied to the search inside the bibliographic databases. Moreover, the authors practiced snowballing technique by complementarily extending their search into the references lists of the selected full-text papers for identifying non-peer-reviewed "grey literature", namely government and multiorganizational reports. Grey literature was extracted via the Google Scholar (GS) web search engine.

The second step of Figure 1 ("Papers editing") comprises the papers' initial identification, the duplicates removal and the choice of the exclusion criteria for refining the exported results. In total, the search yielded 908 peer-reviewed papers from WoS and Scopus databases, from which 124 were duplicates and removed. Afterwards, 700 papers were rejected (either by titles, abstracts and keywords screening or after full-text scrutiny) according to the secondary exclusion criteria of Figure 1 since they were regarded as irrelevant to this study's scope; the shares of the 84 eligible papers according to their different types (e.g., case-study and methodology) are illustrated in Section 3. Thereafter, 37 non-peer-reviewed papers from the GS engine identified. Subsequently, a final refinement was performed for narrowing down the research scope for the review to be focused on the methodological aspect of CBA in the road transport field. Hence, additional qualifying criteria regarding the type of paper were established. Specifically, the survey, discussion and research papers and some organisation reports were excluded since they did not concern the modelling approach aspect and did not add value to the existing body of knowledge regarding the CBA's modelling approaches. Especially, for national guidelines with multiple versions, only the most recent one was included. Ultimately, this process returned 56 papers meeting all the criteria for inclusion in the final analysis; their discrete and cumulative distributions are shown in Section 3. The average trend line shows an upward trend in the research field over the past 15 years.

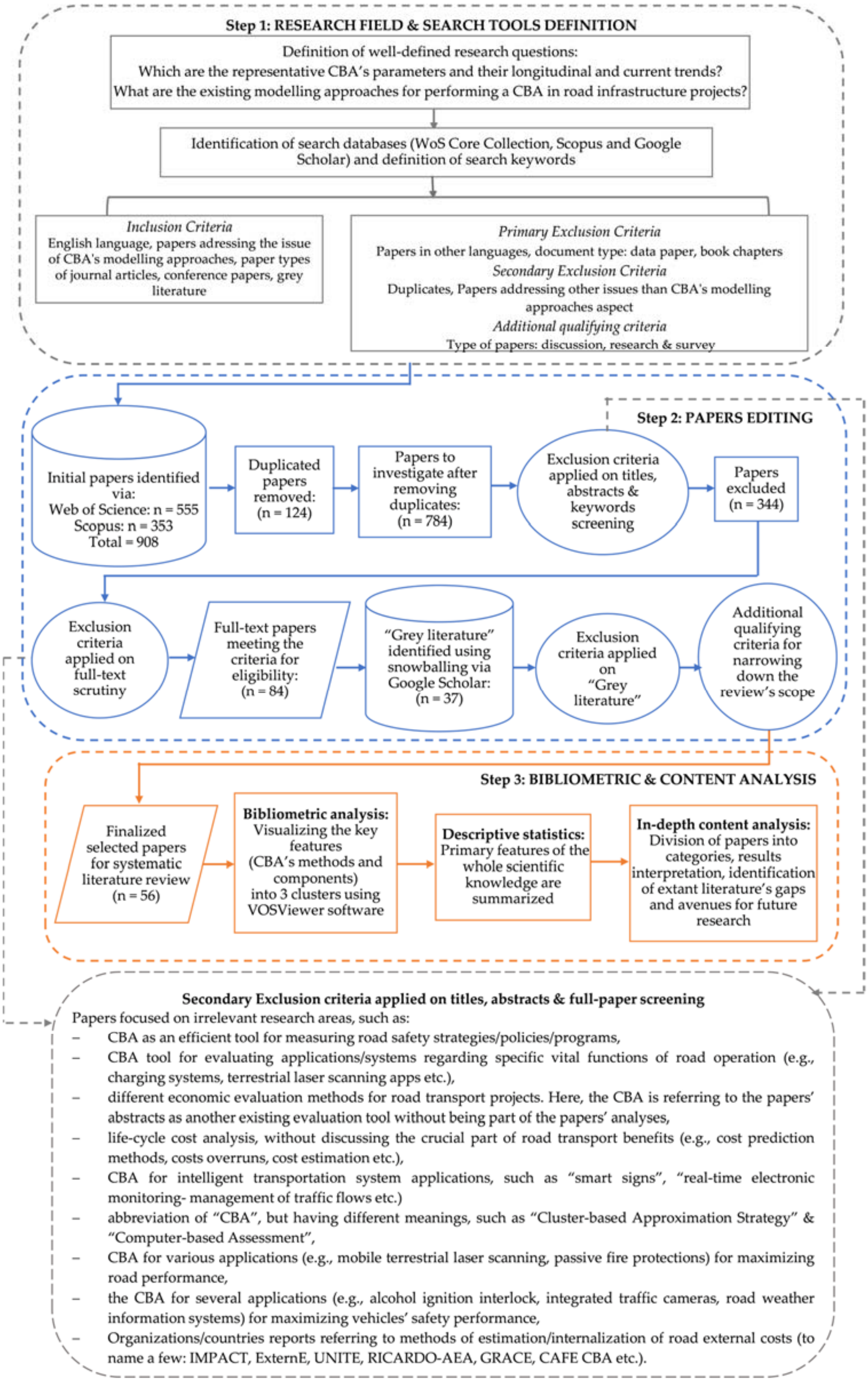

Figure 1. Flowchart for presenting the followed steps for conducting the systematic literature review (SLR), bibliometric and content analysis.

In the third step ("Bibliometric and content analysis"), the entirety of the extracted articles was subjected to BA via VOSViewer software [15]. This robust tool offered the basic-level categorization of the dominant research areas. This policy organized information in a more comprehensible way for the first navigation among the visualized terms by minimizing the complexity of knowledge interpretation derived from different sources.

Subsequently, the selected papers were reviewed and studied one by one to provide a detailed analysis of the current knowledge level and answer the defined questions through content interpretation, gap highlighting and future avenue presentation.

3. Results Bibliometric Analysis and Descriptive Statistics

The scientifically validated map of Figure 2 was created via VOSViewer for optimizing the ease of conception using the 56 retrieved structured papers. The knowledge domain map was plotted using the keyword co-occurrence analysis (parameter settings: type of data: text data, type of analysis: co-occurrence; counting method: full counting; unit of analysis: all keywords). In detail, the textual analysis identified 83 most frequently stated terms as determinants of the CBA method in the road transport field and distinguished three main cognitive clusters (i.e., green, red and blue), which rendered beneficial for revealing the research topic evolution and answering the first question of Figure 1.

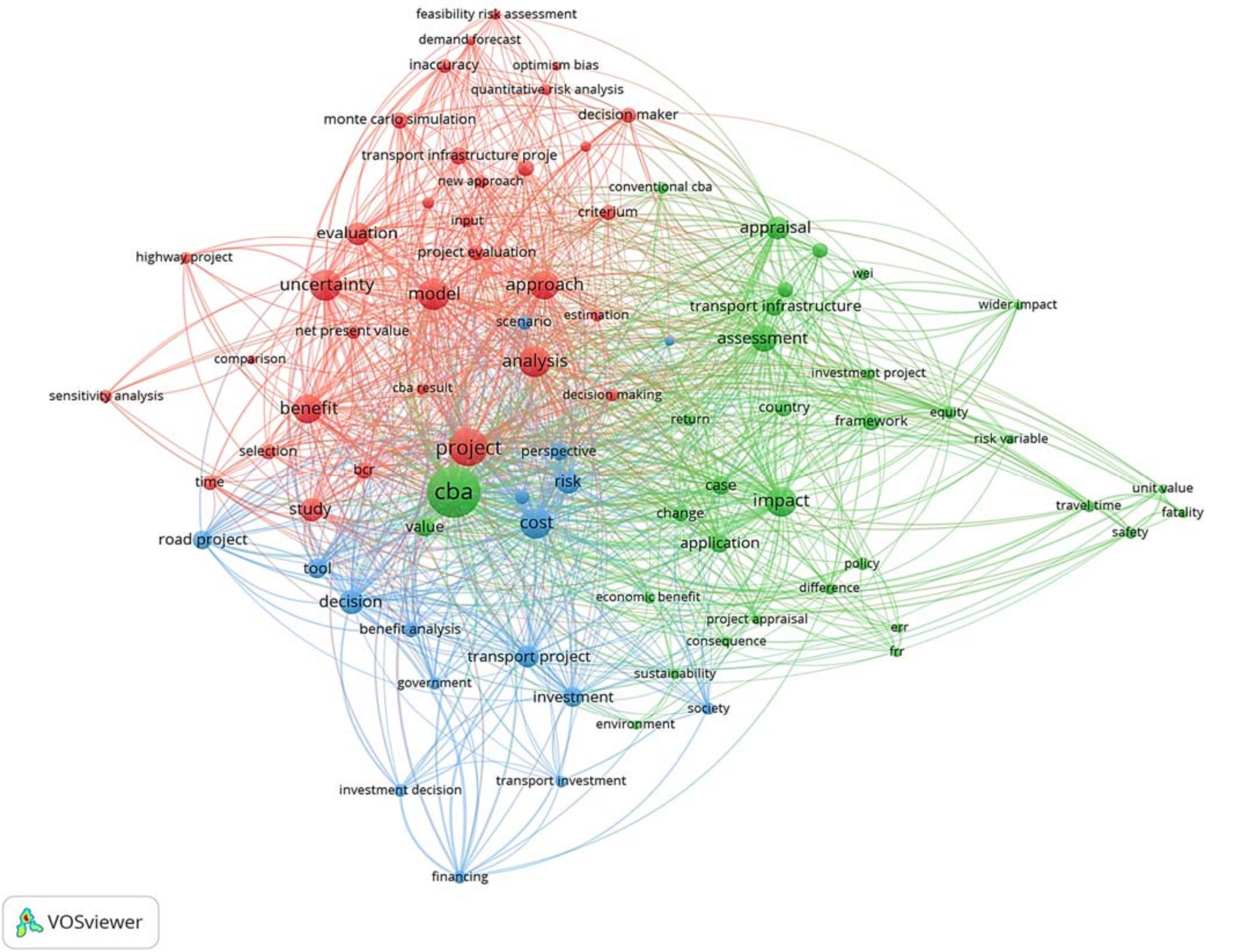

Figure 2. Three main research areas identified via VOSViewer map: (1) A comprehensive framework of individual parts of CBA approach (green cluster); (2) Approaches for incorporating uncertainty within conventional CBA (red cluster); (3) CBA as a decision tool within road project appraisal (blue cluster).

Specifically, the first (green) cluster owned the most numerical keywords occurrences, with the "CBA" term being the most highly reported and forming the core of the present research. Overall, the cluster's peripheral terms constitute the CBA appraisal's satellites and provide a brief historical framework of how these parts co-exist throughout CBA's existence. Initially, a large proportion of the literature recognized the CBA as an assessment model that adopts a partial equilibrium approach referring only to direct impacts—user benefits and external costs (to name a few from the VOSViewer map: changes in travel time, safety, environmental impacts)—that occurred inside the transport market [16–18]. However, since the CBA approach was grounded on traditional microeconomic partial equilibrium theory assuming perfect competition [18], some researchers considered it inadequate for informing decision makers regarding only the primary transport market impacts since the welfare impacts of the investment were not fully measured [19,20].

Therefore, more advocates, such as Koopmans and Oosterhaven [21] were in favour of broadening the CBA scope to incorporate wider economic impacts (WEI) and thus conducting a more representative of the real-world requirements economic appraisal. Overall, the project appraisal was measured using evaluation indicators, such as financial rate of return (FRR) and economic rate of return (ERR). In the second (red) cluster, the highest mentioned term was the "uncertainty" one, revealing its close relation to transport infrastructure project (TIP) evaluation. Increased uncertainty in projects could lower the reliability of cost estimation, thus risk management is regarded as crucial for a project's success [22]. According to the keywords' links, the uncertainty's existence within the CBA approach is caused by three different reasons. The first one is demonstrated due to the embedded risk in all cost and benefits input parameters over the lifetime of the projects [23]. The second reason is the epistemic uncertainty displayed due to the lack of knowledge that can be reduced by empirical efforts [24], while the third one is related to models' errors. Furthermore, it is directly readable from the map's links that the two most prevalent risk analysis methods are sensitivity analysis and the Monte-Carlo simulation (MCS). The latter leans on a repeated random sampling process that improves the contingency of the examined costs [22]. The third cluster (blue) concerns the overall framework since its keywords refer to the CBA as a tool that supports decision making for transport projects by overcoming cognitive and structural limitations and biases [25].

Subsequently, descriptive statistics of the 54 studied papers are presented to provide a preliminary overview of the relative literature (Figure 3); here the two literature review papers were excluded for focusing on methodological approaches. Initially, the used modelling approaches (deterministic, probabilistic, static, dynamic, microeconomic, macroeconomic) for performing CBA for RIPs were classified into eight categories (Mi-D-S, Ma-D-S, Mi-P-S, Ma-P-S, Mi-D-D, Ma-D-D, Mi-P-D, and Ma-P-D category; acronyms are fully explained in Figure 3d). Each category consists of a combination of three distinct modelling approaches, necessary for the CBA's full performance since they investigate separate parts of the CBA procedures. It is worth mentioning that some modelling approaches are mutually exclusive according to the following categorization:

(a) The type of data risk assessment, i.e., deterministic or probabilistic; the former determines single-point estimates for economic indicators such as net present value (NPV) or benefit–cost ratio (BCR). Whereas the latter considers the project's inherent uncertainties and risks, the outputs are obtained via probability density functions (PDFs), showing a range of possible outcomes likely to occur;

(b) The parameters' behaviour in terms of interaction between one another, i.e., static or dynamic; the former indicates that the CBAs components are treated as independent of each other, while the latter considers the interdependencies among CBAs costs and benefits:

(c) The encompassed sectors of economy, i.e., microeconomic or macroeconomic; the former indicates that CBA is founded on traditional microeconomic partial equilibrium assuming perfect competition and only user benefits and environmental impacts are considered, while the latter considers a computable general equilibrium (CGE) model where all influenced economies and wider impacts are assumed.

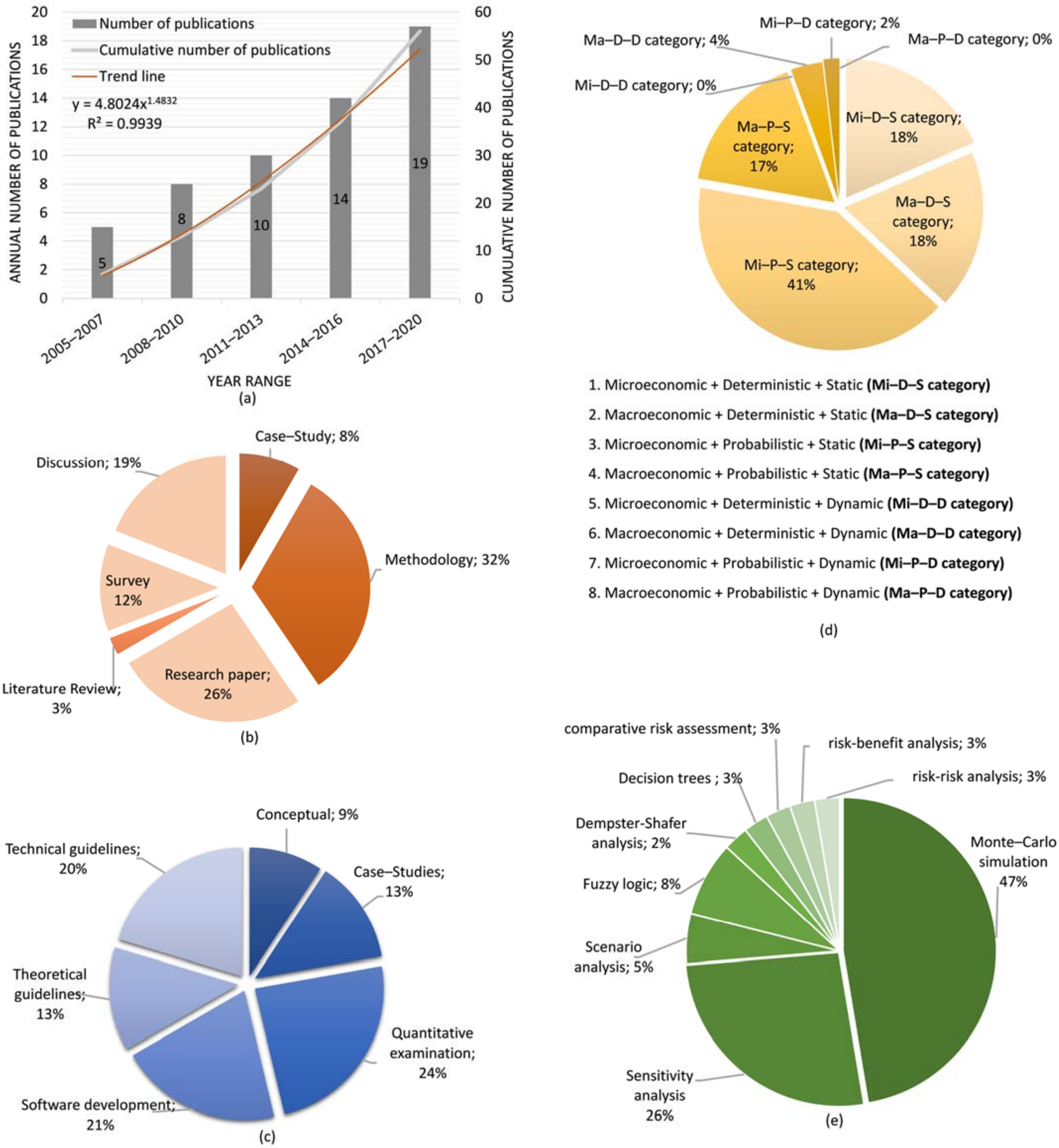

Figure 3. (**a**): Number of publications over the years; (**b**): Pie chart showing the share of different types of papers; (**c**): Pie chart showing paper's scope categorization; (**d**): Pie chart showing the share of different CBA's modelling approaches; (**e**): Pie chart showing the share of different risk assessment methods.

A summary table for the main techniques along with the key characteristics of each modelling approach is provided (Table 1). These attributes are further analysed with the one-by-one paper's investigation in Section 4, which results in current gaps identification and the proposal of future directions in Section 5.

Table 1. Descriptive characteristics of modelling approaches found in the existing literature.

Modelling Approaches	Main Techniques	Main Characteristics	Key Assumptions
		Data analysis methods	
Deterministic	Deterministic mathematical models with fixed values in the variables	Yield single-point output estimates	The randomness or stochasticity of the variables is not taken into account
Probabilistic	Monte-Carlo simulation	Probability density functions are assigned to the input variables and outputs are exported within confidence intervals	Incorporates the uncertainty treating the variables as random ones
	Sensitivity analysis	The impact of one variable on the final outcome is measured by changing the value of the studied variable	All the other variables are remained constant
	Scenario analysis	The combined effect of a change in a whole set of assumptions (e.g., "best/worst", "most likely" scenarios) is analysed	Allows the variation of several variables simultaneously
		Parameters interaction	
Static	Traditional CBA techniques	Provides a 'snapshot' of CBA system's response to a specified set of input variables.	The input–output structure is assumed to remain in a steady state
Dynamic	System Dynamics	Account for interactions among interrelated variables that drive varying behaviour of the CBA system over time	The behaviour of CBA model's variables keeps changing over time
		Considered parameters into the analysis	
Microeconomic	Marshallian consumer's and producer's surpluses	User-benefits and external costs are calculated via generalised transportation costs (Rule of Half)	Partial equilibrium perspective where transport network is treated separately from the broader economy
Macroeconomic	General computable equilibrium models (e.g., Spatial GCEMs, Land Use Transport Interaction models, regional economic models)	Wider economic impacts are incorporated in traditional CBA	Accounting for changes in external markets assuming imperfect competition

According to the pie chart of the combinations of CBAs modelling approaches (Figure 3d), the lion's portion (94%) was held by CBAs approaches in a static environment. Specifically, the Mi-P-S category, namely the combination of microeconomic, probabilistic and static modelling approaches, represents the most significant proportion of the existing approaches, occupying 41% of the total cases. Additionally, the Ma-P-S category accounted for a share of 17%. Hence, it is concluded that three out of five studies (58%) considered uncertainty in a static environment, confirming that probabilistic analysis should be an indisputable part of CBAs. A similar pattern was identified when the combination of deterministic and static approaches was connected either with micro or macroeconomic analyses (Mi-D-S and Ma-D-S categories), accounting totally for approximately one-third of the whole pie (36%).

The remaining small portion of the pie (6%) is distributed among Mi-P-D and Ma-D-D categories, indicating that dynamic approaches are still in the early stages of research. Surprisingly, the number of Ma-P-D and Mi-D-D categories were null.

A different classification of the 54 studied papers was in terms of their scope (Figure 3c). Notably, the proportions of quantitative examination of methods and technical guidelines were quite like each other, accounting for 24% and 20%, respectively. The former refers to papers that introduce a new methodological part in CBA, while the latter contains relevant information and practical explanations of the formulae and equations used in the CBA framework. A relatively equal portion (21%) is also noted for the software development category. Specifically, seven different CBA software were developed (CBA-DK, CLG-DSS, UNITE-DSS, AutoCASE, P3-Value 2.0, CBA6 and Cal-B/C software), whose distinctive features are discussed in the following section. Case-studies papers shared the same amount as theoretical guidelines (13%), with the latter referring to the theoretical basis of CBA, containing a discussion of the important relative issues. All case-study papers implemented commercial software for performing CBA, such as @Risk, Crystal-Ball and HDM. Finally, conceptual papers were accounted for 9% of the whole pie. They referred to a generic framework for any proposed model of CBA, presenting their key features.

4. In-Depth Content Analysis of Modelling Approaches Used for Performing CBA in Road Infrastructure Projects

In this section, the authors reviewed in detail the modelling approaches identified for performing CBA in the road sector. Tables 2 and 3 give an overview of the 54 studied papers, providing a summary of the research objective, the scope for each paper and applied modelling approaches and tools for conducting CBA.

4.1. Studies Performing CBA via the Mi-D-S Modelling Category

This category is the core and the traditional way for performing CBA, serving as the prerequisite ground for the existence of the other categories. Consequently, several sources in the literature (18% of the studied papers) have utilized this method of calculation; papers detailed attributes can be seen in Table 2. Indicatively, DeCorla-Souza et al. [26], Greer and Ksaibati [27] and Uddin and Mizunoya [28] developed Mi-D-S tools for evaluating conventional parameters of CBA, such as reduction of accident, travel time and vehicle operating costs. Sullivan et al. [29] introduced us to a user-friendly Website for properly conducting CBA in an effort of encouraging increased use and suitable application of CBA.

While all the studies reported above highlighted a specific CBA framework, Hanssen et al. [30] investigated how CBAs outcomes differ against the applied model by comparing three different national CBA models from the Nordic countries, concluding that the choice of national model is crucial since different results can derive depending on the model used.

Furthermore, several national authorities and organizations developed practice guidelines for assessing policies via CBA in a Mi-D-S environment. An explicit illustration of these reports can be seen in Table 3, where the "*" symbol indicates guidelines referring to the theoretical basis of the CBA approach, while the "X" symbol indicates guides with formulas and equations used in CBA. Four out of the five national guidelines, Minnesota DOT [31], Transport Infrastructure Ireland [32], UK Department for Transport [33] and World Bank [34], offered technical instructions or theoretical principles concerning consumer surplus, producer surplus and externalities. In contrast, California DOT [35] developed the so-called Cal-B/C software, a Microsoft Excel spreadsheet-based tool that provides economic CBA for a range of TIPs. The basic version of Cal-B/C does not contain risk analysis and it is focused on specific project-based applications, meaning that a series of input variables, namely annual average daily traffic (AADT), international roughness index (IRI), vehicles speed, etc., should be provided by the user for software's running.

4.2. Studies Performing CBA via the Ma-D-S Modelling Category

However, crucial considerations might be lost in conventional CBAs leading to suboptimal investment strategies because, in reality, markets are distorted direct and indirect impacts may differ [20]. Hence, this category seeks to narrow down the gap between actual and captured impacts by incorporating additional impacts ignored in the conventional

CBAs for estimating over and above traditionally measured project's user benefits. The WEIs studied in the literature ranged from economic to environmental to social aspects.

Two extant studies, Calthrop et al. [16] and Kidokoro [36], developed general equilibrium (GE) models to explicitly incorporate all effects of transport investment on all economic markets, advocating that capturing only the direct costs and benefits of an investment may yield misleading unrealistic CBA results. The former [16] considered distortions on all markets and distributional effects for adapting the traditional cost–benefit rules to correct the unrealistic assumptions considered in the conventional CBAs. The latter [36] investigated a basic agglomeration economy model to incorporate the agglomeration effect into conventional CBAs and produce results comparable with conventional CBAs and directly applicable to individual TIPs, such as roads. Accordingly, Laird and Venables [37] recognized the importance of an appraisal framework that ensures all relevant impacts are captured in CBAs beyond conventional benefits. Specifically, they analysed three additional WEIs types, namely the productivity effects, the investment and land-use changes and labour market effects. These WEIs types had been further examined by ITF/OECD [38], which emphasized mechanisms through which transport may create wider benefits and presented well-established methodologies for their comprising into CBAs, as adopted for instance by UK Department for Transport. Moreover, from a UK perspective, OECD/ITF [39] theoretically reviewed the state of WEIs of agglomeration economies, imperfect competition benefits and labour supply effects.

Moreover, Pienaar [40] conducted a regional economic income analysis displaying the significant contribution of the RIP to the primary macroeconomic goal of local wealth. An and Casper [41] conducted CBA combined with regional travel demand analysis using the commercial TREDIS software for evaluating regional transportation projects by examining their economic impacts. Gühnemann et al. [42] developed an innovative procedure for modifying CBA results to facilitate CBA and multi-criteria analysis (MCA) combination as a means of providing a closer alignment between transport policy and the tools used to support projects' effective prioritization.

As regards environmental terms, Manzo and Salling [43] integrated the UNITE-DSS model with a life-cycle assessment (LCA) module for evaluating how the indirect environmental impacts affect the final project evaluation. From the comparison made between CBA's results of the two alternative approaches, namely with and without the LCA module, it was concluded that the LCA module highly affects the CBA's socioeconomic indicators.

From a social point of view, Turró and Penyalver [44] introduced the Intergenerational Redistributive Effects Model (IREM) that incorporate intergenerational fairness into present decisions for detecting investments that could reduce the wellbeing of affected future generations. Contrary to conventional CBAs that assumes that projects are generationally neutral, IREM provides indicators on the intergenerational redistributive effects arising from major TIPs. Thus, IREM is useful to establish to what extend the project's impact is positive for society from a broader perspective than the traditional CBA.

Table 2. Overview of the structured articles extracted from Web of Science (WoS) and Scopus for cost–benefit analysis (CBA) in the road infrastructure sector.

Type of Paper: Case-Study					
Sources	**Research Objective**	**Applied Modelling Approaches for CBA**	**Tools of CBA's Analysis (Key Features) *(Applied Software)***	**Case-Study Application**	**Cluster Identification**
Pienaar [40]	The economic variability of existing and new road sections within feasibility studies	Macroeconomic Deterministic Static	Regional economic income analysis *(HDM-4 software)*	Real-world case-specific road; Namibia	1
Del Giudice et al. [45]	Reducing the level of uncertainty within feasibility studies of road infrastructure project (RIP)	Microeconomic Probabilistic Static	Monte-Caro simulation (MCS) Probability density functions (PDFs) of uncertain inputs: "Travel time savings": Normal "investment cost": Triangular PDFs defined by experts; low level of knowledge (LoK) *(@Risk software)*	Real-world case-specific road; Italy	2
Korytárová and Papežíková [46]	Estimating the inaccuracy of economic efficiency ratios in ex-ante road appraisals	Microeconomic Probabilistic Static	MCS Uncertain inputs: "traffic forecast" *(Crystal-Ball software)*	27 real-world samples; Czech Republic	2
Varbuchta et al. [47]	Specifying new risk variables in the transport infrastructure project (TIP) assessment	Microeconomic Probabilistic Static	MCS Uncertain inputs: "external costs": triangular PDF defined by experts; low LoK	Real-world case-specific road; Czech Republic	2
Prakash [48]	Capturing crash cost savings in CBAs	Microeconomic Probabilistic Static	MCS Uncertain inputs: "estimated crash number": Bernoulli PDF defined by experts; low LoK *(@Risk software)*	Theoretical case	1
Vagdatli and Petroutsatou [23]	Evaluating non-revenue infrastructure projects for European co-financing eligibility	Microeconomic Probabilistic Static	MCS Uncertain inputs: "annual average daily traffic" (AADT) and "investment cost"; triangular PDF defined by experts; low LoK *(@Risk software)*	Real-world case-specific road; Greece	2

Table 2. *Cont.*

Type of Paper: Case-Study					
Sources	**Research Objective**	**Applied Modelling Approaches for CBA**	**Tools of CBA's Analysis (Key Features) *(Applied Software)***	**Case-Study Application**	**Cluster Identification**
Uddin and Mizunoya [28]	Estimating CBA's key parameters and evaluating economic variability of a proposed RIP	Microeconomic Deterministic Static	*(HDM software)*	Real-world case-specific highway; Bangladesh	1
Type of Paper: Methodology					
Sources	**Research objective**	**Applied modelling approaches for CBA**	**Proposed method of CBA's analysis (Key features) *(Proposed model's name)***	**Scope:** -Conceptual -Quantitative examination -Software development *(Case-study, if any)*	**Cluster identification**
Sullivan et al. [29]	Web-based guide proper application of CBA in transport investment decisions	Microeconomic Deterministic Static	*(Cal-B/C Sketch and Cal-B/C Corridor software)*	Conceptual	3
Li and Madanu [49]	Handling certainty, risk and uncertainty in CBAs of highway projects	Microeconomic Probabilistic Dynamic	MCS Uncertain inputs: "construction", "maintenance", "traffic growth rates", "discount rate"; Beta PDF defined by Indiana historical data between 1990–2006; high LoK	Quantitative examination *(7380 highway projects; Indiana state)*	2
An and Casper [41]	Estimating B/C ratio for RIP adopting a regional travel demand model and CBA	Macroeconomic Deterministic Static	Regional travel demand model	Quantitative examination *(4 real-world samples; Pikes Peak region)*	1
Calthrop et al. [16]	Adjusting CBA for considering markets' distortions and distributional effects	Macroeconomic Deterministic Static	General equilibrium (GE) model	Quantitative examination *(Theoretical case)*	3

Table 2. *Cont.*

Type of Paper: Case-Study					
Sources	**Research Objective**	**Applied Modelling Approaches for CBA**	**Tools of CBA's Analysis (Key Features) *(Applied Software)***	**Case-Study Application**	**Cluster Identification**
Kidokoro [36]	Clarifying the incorporation of the agglomeration effect into conventional CBA	Macroeconomic Deterministic Static	General equilibrium (GE) model	Quantitative examination	1
Maravas et al.; Maravas and Pantouvakis [50,51]	Modelling inherent uncertainty of TIP into CBA	Microeconomic Probabilistic Static	fuzzy set theory	Quantitative examination *(Theoretical case)*	2
Gühnemann et al. [42]	Developing a tool for supporting effective project prioritization in compliance with strategic goals	Macroeconomic Deterministic Static	CBA combined with multi-criteria analysis (MCA); Inputs: conventional benefits; Wider economic impacts (WEIs) and non-monetized impacts	Quantitative examination *(A real-world network; Ireland)*	1
DeCorla-Souza et al. [26]	Presenting a three steps CBA frame for Public-Private Partnership (PPP) highway concession proposals evaluation	Microeconomic Deterministic Static	Project delivery Benefit–Cost analysis (PDBCA); *(P3-Value 2.0 software)*	Software development *(Theoretical case)*	3
Salling and Leleur [24,52]	Introducing a new software for assessing TIP using risk-CBA	Microeconomic Probabilistic Static	MCS PDFs of uncertain inputs: "construction costs": Gamma, "travel time savings": Normal, "maintenance cost": Triangular, "accident unit price": Uniform; PDFs derived from previous studies; medium LoK *(CBA-DK software)*	Software development	2
Salling et al. [53]	Presenting a new CBA-based decision support system for assessing uncertainties of TIPs	Macroeconomic Probabilistic Static	MCS Combined with MCA, scenario analysis (SA) *(CLG-DSS software)*	Software development *(Real-world case-specific application)*	2

Table 2. *Cont.*

Type of Paper: Case-Study					
Sources	**Research Objective**	**Applied Modelling Approaches for CBA**	**Tools of CBA's Analysis (Key Features) *(Applied Software)***	**Case-Study Application**	**Cluster Identification**
Salling [54]	Handling construction costs and demand forecasts inaccuracies of TIP in CBA	Microeconomic Probabilistic Static	MCS and Reference Class Forecasting (RCF) PDFs of uncertain inputs: "construction cost": Erlang; "demand forecast": Normal; PDFs defined by UNITE database; high LoK *(UNITE-DSS model)*	Software development *(Real-world case-specific fixed-link application; Denmark-Sweden)*	2
Salling and Leleur [55,56]	Examining construction costs and demand forecasts inaccuracies throughout TIP evaluation	Microeconomic Probabilistic Static	MCS and RCF Uncertain inputs: "construction cost"; "demand forecast"; PDFs defined by UNITE database; high LoK *(UNITE-DSS model)*	Software development *(4 real-world samples, each from different types of TIPs)*	2
Manzo and Salling [43]	Clarifying the indirect environmental impacts into the standard CBA results	Macroeconomic Deterministic Static	Life-cycle assessment (LCA) combined with UNITE-DSS model	Quantitative examination *(Real-world case-specific fixed-link; Denmark)*	3
Parker and Rommelaere [57]	Integrating the travel time reliability into the CBA	Macroeconomic Probabilistic Static	WEI: travel time reliability MCS; *(AutoCASE model)*	Software development	1
Bağdatlı et al. [58]	Dealing with uncertainty in highway CBA via a new approach	Microeconomic Probabilistic Static	Fuzzy cognitive map	Quantitative examination *(Real-world case-specific application)*	2

Table 2. *Cont.*

Type of Paper: Case-Study					
Sources	**Research Objective**	**Applied Modelling Approaches for CBA**	**Tools of CBA's Analysis (Key Features) *(Applied Software)***	**Case-Study Application**	**Cluster Identification**
Salling and Banister [59]	Presenting the final version of a new decision support model of risk CBA for TIP assessment	Microeconomic Probabilistic Static	MCS PDFs of uncertain inputs: "traffic forecast": Pert defined by 183 road projects, "construction costs": Erlang defined by 167 infrastructure projects; high LoK *(CBA-DK software)*	Software development	2
Shiau [60]	Handling uncertainty and incorporating incomplete information into the TIPs evaluation	Macroeconomic Probabilistic Static	Multicriteria decision analysis (MCDA) and Dempster–Shafer Theory	Quantitative examination *(Real-world case-specific application; Taiwan)*	2
Nguyen et al. [61]	Capturing the dynamic relationships between CBA components over time	Macroeconomic Deterministic Dynamic	ABM, System Dynamics (SD) and multi-criteria method (MCM)	Conceptual	1
Rothengatter [18]	Analyzing WEIs measurement and their connection with conventional CBA	Macroeconomic Deterministic Dynamic	Spatial computable general equilibrium (SCGE), Macro and regional economic models, System dynamics, Integrated assessment models, Separated measurement formulas	Conceptual	1
Laird and Venables [37]	Broadening the scope of conventional CBAs by incorporating three types of WEIs	Macroeconomic Deterministic Static	WEIs: productivity; private investment and land use change; labour market	Conceptual	1
Nguyen et al. [62]	Presenting an enhanced CBA framework with six functions and four main processes for project evaluation	Microeconomic Probabilistic Static	Enhanced CBA framework	Conceptual	1

Table 2. *Cont.*

Type of Paper: Case-Study					
Sources	**Research Objective**	**Applied Modelling Approaches for CBA**	**Tools of CBA's Analysis (Key Features) *(Applied Software)***	**Case-Study Application**	**Cluster Identification**
Turró and Penyalver [44]	Assessing the usefulness of major TIPs to future generations	Macroeconomic Deterministic Static	Intergenerational Redistributive Effects Model (IREM) model	Quantitative examination *(3 real-world samples; Spain)*	1
Greer and Ksaibati [27]	Developing CBA tools to assist transportation agencies in the estimation of benefits of TIP	Microeconomic Deterministic Static	CBA combined with LOS	Quantitative examination *(3 real-world samples)*	3
Hanssen et al. [30]	Investigating to what extent CBAs outcomes differ against the applied model	Microeconomic Deterministic Static	*(EFFEKT, EVA and IVAR models)*	Quantitative examination *(Theoretical case)*	1

Table 3. Overview of the grey literature extracted from Google Scholar (GS) for CBA in the road infrastructure sector.

Sources	**Scope: Theoretical Guidelines Technical Guidelines Software Development**	**Applied Modelling Approaches for CBA**	**Producer Surplus**	**Consumer Surplus (Users Benefits)**	**Externalities**	**WEI**	**Non-Monetized Impacts**	**Risk—Uncertainty**
World Bank [34]	Technical	Microeconomic Deterministic Static	X	X	*			
OECD [63]	Technical	Macroeconomic Probabilistic Static	X	X	X	X		*
Treasury Board of Canada [64]	Theoretical	Microeconomic Probabilistic Static	*	*	*		*	*

Table 3. *Cont.*

Sources	Scope: Theoretical Guidelines Technical Guidelines Software Development	Applied Modelling Approaches for CBA	Producer Surplus	Consumer Surplus (Users Benefits)	Externalities	WEI	Non-Monetized Impacts	Risk—Uncertainty
OECD/ITF [39]	Theoretical	Macroeconomic Deterministic Static	*	*	*	*		
OECD/ITF [65]	Theoretical	Microeconomic Probabilistic Static	*	*	*			*
State of Queensland [66]	Software development *(CBA6 software)*	Microeconomic Probabilistic Static	X	X	X			X
Transport Infrastructure Ireland [32]	Technical	Microeconomic Deterministic Static	*	X	*		*	
Minnesota DOT [31]	Technical	Microeconomic Deterministic Static	*	X				
European Investment Bank [67]	Technical	Macroeconomic Probabilistic Static	X	X	X	*		X
Asian Development Bank [68]	Technical	Microeconomic Probabilistic Static	X	X	*			X
European Commission [69]	Technical	Microeconomic Probabilistic Static	X	X	X			X
UK Department for Transport [33]	Theoretical	Microeconomic Deterministic Static	*	*				

Table 3. *Cont.*

Sources	Scope: Theoretical Guidelines Technical Guidelines Software Development	Applied Modelling Approaches for CBA	Producer Surplus	Consumer Surplus (Users Benefits)	Externalities	WEI	Non-Monetized Impacts	Risk—Uncertainty
British Columbia [70]	Theoretical	Microeconomic Probabilistic Static	*	*	*			*
Queensland Treasury [71]	Theoretical	Microeconomic Probabilistic Static	*	*	*			*
ITF/OECD [38]	Technical	Macroeconomic Deterministic Static				X		
California DOT [35]	Software development *(Cal-B/C software)*	Microeconomic Deterministic Static	X	X	X			
United Kingdom HM Treasury [72]	Technical	Macroeconomic Probabilistic Static	*	*	X	X	*	*
Commonwealth of Australia [73]	Technical	Macroeconomic Probabilistic Static	*	X	X	*	*	X
Transport of New South Wales [74]	Theoretical	Macroeconomic Probabilistic Static	*	*	*	*		*
AIReF [75]	Technical	Macroeconomic Probabilistic Static	X	X	X	X		*

Note: Reports that have developed quantitative approaches even in one of their individual components have been classified as "Technical guidelines". * symbol indicates guidelines referring to the theoretical basis of the CBA approach. X symbol indicates guidelines using technical approaches, such as formulas and equations for presenting the CBA approach.

The three combined modelling approaches discussed in this section have gained the most attention in the extant literature (41% of the studied papers), as they overcome the limitation of fixed values reports considering the project's inherent uncertainty and yield more reliable results by reflecting the whole spectrum of output variables.

Until the mid-2000s, the road infrastructure field lacked a generally approved comprehensive way of combing CBA with quantitative risk analysis (QRA). The first attempt to provide risk-based CBA of RIPs was conducted by Salling and Leleur [24,52]. They introduced an Excel-based software, the so-called CBA-DK model, for assessing TIPs combing deterministic CBA with MCS via @Risk software. In this way, decision makers could have more profound and informed knowledge since CBAs' outputs were presented within confidence intervals rather than single-point estimates. A set of suitable PDFs (Table 2), defined by a PhD thesis [76] for critical input variables into the CBA-DK framework, was used. In general, for running QRA into the CBA-DK, users should choose the PDF type among those available and define their specific parameters, thus limiting its use to those who have detailed knowledge for producing a high level of knowledge (LoK) PFD for each input parameter in order to avoid bias issues derived from low LoK PDFs.

Hence, a special issue recognized by Salling and Banister [59] was the pursuit of the most representative PDFs for capturing the inherent uncertainty of input parameters into the CBA-DK framework. The authors proposed the Reference Class Forecasting (RCF) method for shifting the LoK concerning processing uncertain input variables from a low LoK to a high one by expressing the variables with a statistical distribution formulated by similar projects values. Using a TIPs historical dataset collected by twenty nations from [77], they export PDFs for construction costs and traffic forecasts variables, as can be seen in Table 2. Thereafter, Salling and Salling and Leleur [54–56] presented the UNITE-DSS, an Excel-based decision support model, which contains an integrated approach to socio-economic analysis, risk-based simulation and the so-called UP database containing almost 200 specific European TIPs (e.g.,: roads, fixed-links, rails) between 2009–2013. Again, among various CBA's inputs, construction costs and demand forecasts were proven to be affected by a substantial degree of uncertainty and their PDFs were further examined for obtaining reliable estimates (Table 2).

Furthermore, various "case-study" papers performed traditional CBA combined with MCS each of them examining a specific objective within roads' economic evaluation (Table 2). All these papers used commercially available risk assessment tools integrated with Microsoft Excel that can be applicable for RIP evaluation, such as @Risk and Crystal-Ball software. Particularly, Korytárová and Papežíková [46] estimated the total inaccuracy of economic efficiency ratios calculation in ex-ante project appraisals using QRA and noted that the benefits inaccuracies between ex-ante and ex-post approaches presented very inconsistent results, with the travel time savings occupying the largest share of inaccuracy among studied benefits. Del Giudice et al. [45], Prakash [48], Vagdatli and Petroutsatou [23] and Varbuchta et al. [47] supported that probabilistic CBAs of RIPs render the evaluation process more transparent and responsible since they provide additional information to the decision makers compared to the deterministic ones. All these papers used PDFs with low LoK (Table 2), while the last two acknowledged that a database of similar projects would be beneficial for extracting more appropriate PDFs for input variables, leading to more robust probabilistic NPV results. Except for the well-established MCS used for copying with uncertainty of RIPs, some authors considered the uncertainty in the CBA models using alternative risk-based procedures. Maravas et al. and Maravas and Pantouvakis [50,51] presented an alternative mathematical approach based on fuzzy set theory for modelling the inherent uncertainty of TIP into CBA. They concluded that fuzzy-CBA is much easier to computerize than MCS obtaining useful results very quickly. Likewise, Bağdatlı et al. [58] investigated the utility of a fuzzy cognitive map approach for minimizing the effects of uncertainty in highway CBAs. Nguyen et al. [62] presented an enhanced functional CBA framework providing six functions and four main processes regarding the holistic picture of project evaluation.

Additionally, there is a broad grey literature covering the issue from a Mi-P-S perspective. Seven government and organizational reports incorporate risk analysis into the CBA framework and provide either theoretical or technical guidelines for accomplishing it (Table 3). Four of these reports, British Columbia [70], OECD/ITF [65], Queensland Treasury [71] and Treasury Board of Canada [64], were conceptually compiled, referring solely to the conventional impacts and risk analysis being addressed in the structure of CBA within Canadian, Mexican, Australian and British Columbia framework, respectively. All these guides reported sensitivity analysis as a method for considering uncertainty, while British Columbia [70] added the scenario analysis (SA) and the Treasury Board of Canada and Queensland Treasury [64,71] added the MCS for risk assessment. From a quantitative assessment point of view, the Asian Development Bank and European Commission [68,69] offered methods for sensitivity analysis and MCS for identifying projects' critical variables, allocating appropriate PDFs to them and performing QRA. Finally, the State of Queensland [66] proposed a PC-based tool, the so-called CBA6 software, for evaluating rural and urban RIPs. As in the case of Cal-B/C software, CBA6 performs project-based CBA, implying that a series of input variables—namely AADT, vehicles speed, road length, life-cycle costs, etc., should be provided by the user for software's running. Regarding the risk analysis, CBA6 conducts sensitivity analysis for some specific input variables, such as vehicle operating cost and travel-time savings.

4.3. Studies Performing CBA via the Ma-P-S Modelling Category

Articles in this category differ from those in the previous one only in terms of the examined markets, namely they consider a macroeconomic approach considering the interaction between the transport sector and the overall economy. The two approaches that complement the analysis remain probabilistic and static.

Two studies, Salling et al. and Shiau [53,60] combined CBA and MCA for assessing a macroeconomic set of distributional and other impacts under uncertainty. The former [53] presented a special hybrid version of the CBA-DK, the Excel-based CLG-DSS model, for decision makers to be facilitated to assess various uncertainties of TIPs. This model consisted of two modules, the COSIMA-module (CBA and MCA combination) and the computable general equilibrium (CGE) model. Their coupling was regarded as well-suited to address both the direct and indirect effects of TIPs. They examined the WEIs of network and mobility, employment and logistics and goods effects. Ten different scenarios regarding the regime of the market mechanism were considered in the CLG-DSS model, with MCS via @RISK software to be used for handling uncertainty. The latter [60] introduced a hybrid approach using the Dempster–Shafer theory for handling uncertainty due to missing information and synthesized monetary and non-monetary criteria into a utility unit. Moreover, Parker and Rommelaere [57] synthesized a reliability ratio for integrating the travel time reliability into the CBA as an additional benefit of TIPs and created the AutoCASE model, a commercial version of the proposed models applicable in the USA and Canada regions. All model's results were presented in probabilistic terms using MCS.

Six national guidelines addressed the CBA in Ma-P-S terms. Table 3 shows if CBA's sections are presented theoretically or technically. In five out of six national guidelines (European Investment Bank [67], United Kingdom HM Treasury [72], Commonwealth of Australia [73], Transport of New South Wales [74] and AIReF [75]) the most common techniques for risk were sensitivity and full risk analysis, with the latter making use of MCS for providing a comprehensive picture of the potential variability of a project. Additionally, decision trees [72] and SA [75] completed the reported set of risk analysis techniques. OECD [63] analysed except sensitivity analysis and various other techniques for risk assessment, such as comparative risk assessment, risk–benefit analysis, and risk–risk analysis. Furthermore, equity [63] and distributional effects [73] were among the most highly reported WEIs.

4.4. Studies Performing CBA via the Mi-P-D and Ma-D-D Modelling Category

This section presents articles that dynamically approach the CBA, regardless of how they operate in terms of data risk assessment and considered markets since these articles are scarce (6% of total cases) and unable to be divided into independent subsections; the full categorization of the articles can be seen in Table 2.

Two articles considered the Ma-D-D perspective for performing CBA (4% of the total cases). Nguyen et al. [61] introduced a hybrid conceptual framework for capturing the dynamic relationships between CBA's costs and benefits over time, using a combination of agent-based modelling (ABM) and System Dynamics (SD) with multi-criteria method (MCM). The first two approaches captured the behaviour of the heterogeneous agents in the transport, supply chain system and real estate market leading to a macroeconomic consideration of CBA and examined the socioeconomic factors and their relationships. Rothengatter [18] presented various approaches for WEIs measurement and analysed the usefulness of connecting them with conventional CBA. Among the analysed approaches was the SD, which allows the investigation of dynamic relationships between the elements in order to understand complex systems and their development in space and time.

A crucial feature of most of the extant literature is that "risk" and "uncertainty" terms were interchangeably used when conducting probabilistic CBA. Only Li and Madanu [49] separated the two concepts and proposed a new methodology for highway project life-cycle CBA, which except for certainty analysis, introduced risk analysis for input variables with known probabilities and uncertainty analysis for inputs with unknown probabilities. Under a Mi-P-D environment, they approached the dynamic relationship among the examined annual maintenance and user costs using a geometric growth rate between two successive treatment intervals based on the first year's values for each interval.

5. Gaps of CBA Approach and Future Research Directions

As a result of in-depth content analysis, the authors identified gaps in the main modelling approaches summarized below, along with directions for future research:

5.1. Model's Probabilistic Imputs Updating

Among probabilistic methods used for risk assessment within CBAs models, the MCS gained ground and became the most widely used method longitudinally for handling uncertainty and exporting results within confidence intervals (47% of Figure 3e cases). The remaining approaches, except fuzzy logic, do not perform full probabilistic analysis for exporting PDFs but scenario analysis for specific values given a probability. Although it is well-documented that some limitations regarding the accuracy of inputs PDFs into MCS have been filled by new studies, what is yet missing is a straightforward way to update model parameters in the light of new evidence. Since there is no interactive link between data and output variables in MCS, model parameters can be updated via a reasonably complex, iterative process that requires new simulation. Such validation is frequently arbitrary because more than one combination of parameter values may yield similar output [78]. Therefore, this probabilistic approach is robust when PDF types of inputs are already known, but this is often not the case.

A good alternative to overcome this problem regarding inputs variability is to apply Bayesian analysis. This method is generally superior to an MCS primarily because it can combine different sources of information, namely experts' judgment (prior distribution) and actual data (likelihood function), formulating a posterior distribution using the Bayes inference [78]. Moreover, if additional data are available for a given model's parameter, its posterior distribution is updated given the new evidence, keeping the system constantly informed [79]. Furthermore, a special feature of Bayesian networks (BNs) is that they provide an intuitive graphical visualisation of the knowledge, including the interactions among the various sources of uncertainty. Consequently, BNs can be used to both display the effects of input variables' changes on output variables (forward propagation) and, if desired, the effects of output variables' changes on the PDFs of preceding variables (backward propagation) with great simplicity.

5.2. Dynamic Interdependent Framework

With the partial exception of three papers (Rothengatter [18], Li and Madanu [49] and Nguyen et al. [61]) the bulk of the studied papers investigated the topic from a static viewpoint, revealing the scarcity of dynamic approaches mainly due to two reasonable reasons. From a modelling point of view, interrelations between model's parameters make the whole system much more complex, while from a practical perspective, the actual measurement of the interdependencies among parameters stands difficult. However, since the service life of road infrastructure extends over several decades, its service level does not remain unchanged due to natural and human deterioration factors [80]. In an evolutionary environment such as this, the static CBA approach may result in misleading economic outputs since the variations caused to the financial (construction, operation and maintenance) and economic (user) annual costs by the crucial factor of their interdependencies are remaining uncaptured.

From the three sources dealt with the dynamic nature of CBAs approaches, two examined the issue conceptually from a macroeconomic aspect without considering the uncertainty. Only one Mi-P-D study [49] assumed a geometric growth rate for the longitudinal variation of critical parameters, such as maintenance and user costs, demonstrating that any form of road treatment cannot leave the user's impacts unaffected. Yet, none provided a specific empirical correlation structure, derived from real-world observations, regarding the dynamic interrelation among the model's parameters and how one's actual change could affect both other parameters behaviour and the final outcome.

5.3. Homogenous Data Collection and Componentization of Road Assets

Moreover, five out of thirty-two studied papers used a pool of transport projects for applying risk-based CBA models (Li and Madanu [49], Salling and Banister [59], Salling [54] and Salling and Leleur [55,56]). The first paper used a database of 7380 Indiana highway projects, the second used a historical TIPs dataset of 20 nations, while the UP database, containing 200 TIPs, was utilized by the three remaining papers. Even though each contract details are confidential and are presented as black box information in articles, making the homogeneity of the historical data challenging to judge, the relatively giant number of these projects deriving from different countries suggests the heterogeneity of the samples in terms of projects' key features such as lanes, length and AADT. Even if there is a differentiation between mode types (e.g., road, rail and fixed links), there is still a further need for classification into specific road functional categories (e.g., highways, other principal arterials and collectors) as well as independent categories of tunnels and bridge to formulate homogenous datasets for providing more reliable decision making, since aggregated data from all type categories lead to misleading cost results, inept of being used as a reference point for future projects. Moreover, it is unattainable for these publications to involve the system's dynamics (as explained in Section 5.2) since their costs are not fragmented into individual categories (roads, tunnels and bridges) and project components.

5.4. Proposed Conceptual Model for Future Research

As stated in the previous sections, the existing software are project-oriented since users should determine a number of inputs specific for each project (AADT, lanes, PDF types, life-cycle costs, etc.) for running the simulation and obtaining the final outcome. Hence, neither software's outcome can be generalized for representing a category of similar projects. This limitation along with the above three specified gaps trigger future work on the development of a generalized model for conducting CBA for RIPs within a microeconomic, probabilistic and dynamic framework; illustratively, the authors propose the conceptual framework depicted in Figure 4, which full development and explanation are into the scope of future publication.

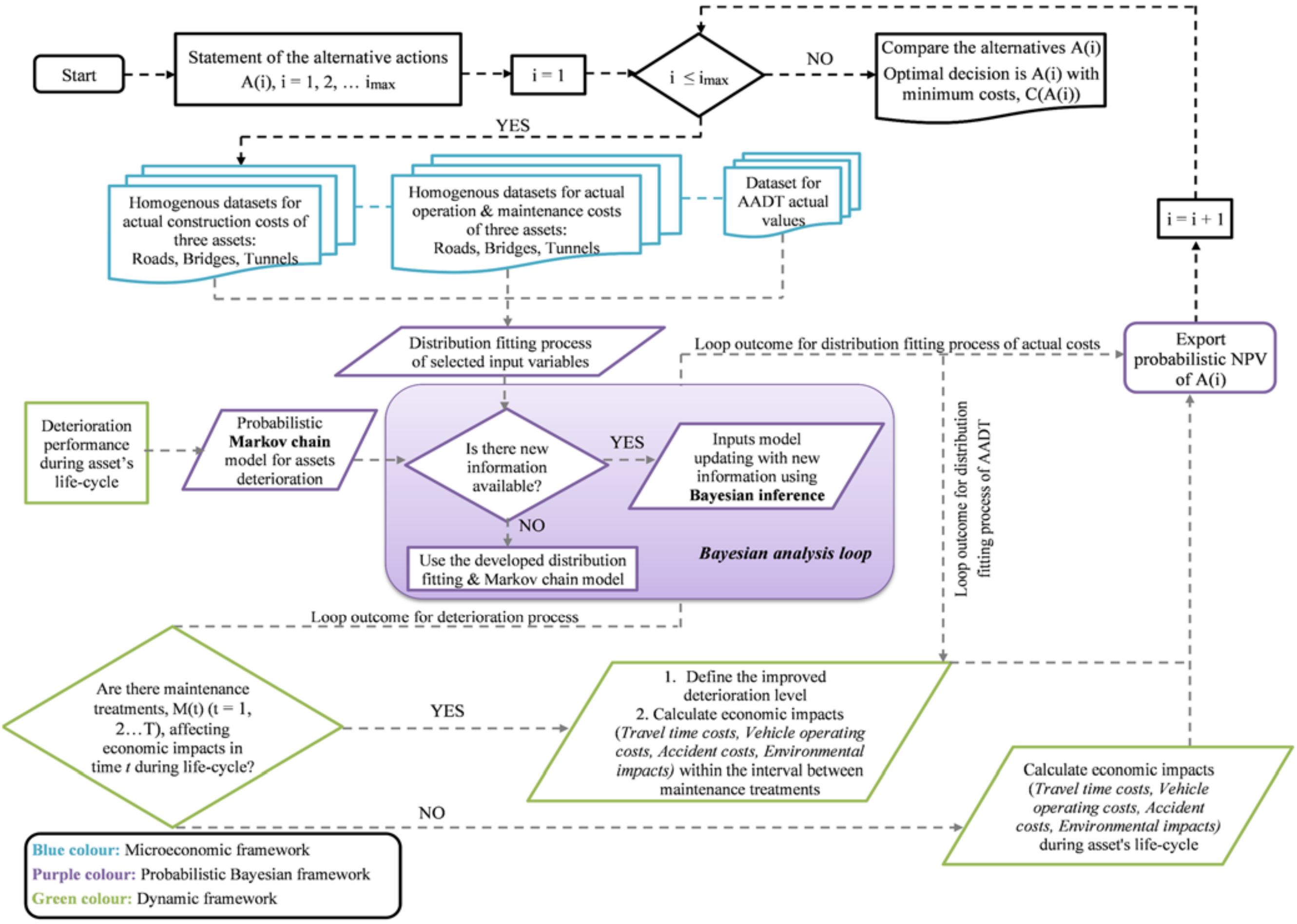

Figure 4. Proposed conceptual framework for a microeconomic, probabilistic and dynamic model for performing CBA Conclusion.

Since cost information is sensitive and thus limited and difficult to be gathered, one significant key attribute of this model is the detailed collection of actual cost datasets from a homogenous environment of similar projects for individual assets such as roads, bridges and tunnels for life-cycle cost analyses. This could ensure that nearly all cost deviations will be related to the project's studied independent variables with very little disturbance from exogenous factors [81], such as noise of various countries' tax regimes and other payment policies. Moreover, by fragmenting the costs into individual categories, the interdependencies between the financial and economic cash flows could be investigated (in particular, if one component is improved via maintenance treatments, this will affect the economic impacts and, thus, the final cashflows of the whole CBA study), leading to the integration of dynamics of systems into the CBA's examination. Furthermore, when conducting probabilistic CBA, the more precise the definition of the random input PDFs, the more closely the simulation model mimics real-life conditions [79]. In the proposed model, these databases will be constantly enriched with new data from managers or constructors after authorized audit via Bayesian analysis for capturing real-world uncertainty. Overall, the proposed CBA model will perform into a dynamic interdependent programming environment (e.g., dynamic Bayesian network or ABM), that will consider the interlink between financial and economic costs over the life-cycle of each asset.

6. Conclusions

The issue of road infrastructure evaluation has always constituted a meaningful research field due to its importance in the decision-making process. This paper provided a comprehensive SLR of 56 selected CBA papers focusing on the methodological perspective of the CBA of RIPs. The BA divided the entire CBA's literature into three representative clusters and along with the descriptive statistics provided an overview of the whole scientific knowledge and key issues concerning CBA approaches till today. Specifically, the CBA's existing modelling approaches were classified into eight categories. Each category was comprised of a combination of three distinct modelling approaches regarding the type of data risks assessment, the interrelation among CBA's parameters and considered economy's sectors respectively. By far the most analysed category was the Mi-P-S one, while Ma-P-D and Mi-D-D categories were not studied in the literature.

From the in-depth content analysis, three gaps were recognized to be diffused among the studied literature body regarding the CBA's probabilistic approach, variables dynamic interrelation and homogeneity of used databases, supporting the argument that existing models require further improvements and structural changes to facilitate decision making reliably. Therefore, this paper intended to fill a crucial gap in the literature on life-cycle cost–benefit estimation since the above limitations paved the way for the conceptual model proposed, where CBA is investigated within a microeconomic, probabilistic and dynamic framework.

Three primary future directions to fill the gaps and evolve the CBA's modelling approaches were derived from this study. In summary, considering the prevailing uncertainty in a project's whole life cycle, cost predictions are more trustworthy if they are updated given any further available data, thus improving decision making in the feasibility phase of the projects. Bayesian analysis was proposed for capturing the inherent uncertainty of CBAs variables since it has a comparative advantage against MCS in terms of inputs variables updating with new data, as well as its two sides propagation, forward and backward. Furthermore, it was observed that the complexity of the issues related with interrelations among CBAs parameters led most of the studies to assume static approach. However, when performing static CBA, there is a substantial bias in the output indicators, since this approach does not represent actual conditions, thus a more realistic scenario should be adopted. Hence, the proposed conceptual model will operate into a dynamic programming environment (e.g., dynamic Bayesian networks or ABM environment). Moreover, since cost datasets are sensitive and rarely published, there is an imperative need for using homogenous datasets regarding the costs and benefits of RIPs for certifying reliable decision making when conducting life-cycle analysis estimations. In conclusion, the results of this study could contribute to the engineering practitioners and project managers with useful insights towards an upgrade and a more comprehensive way of conducting CBAs by eliminating bias caused by uncaptured information.

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Appendix A

Table A1. Literature search syntax used in WoS and Scopus databases.

WoS: "Topic" field *Scopus: "TITLE-ABS-KEY" field*
"cost–benefit analys *" OR "cost benefit analys *" OR "benefit cost analys *" OR "CBA *" OR "BCA *" OR "Life-cycle cost–benefit analysis" OR "LCCBA"
AND
road OR highway OR freeway OR transport * infrastructure OR transport * investment * OR infrastructure project *
NOT
"rail *" OR "airport *" OR "water" OR "aviation *" OR "cycli *" OR "bus *" OR "building *" OR "health *" OR "metro" OR "urban"

Note: The asterisk (*) wildcard was used in the bibliographic databases search for finding any group of characters (including no character) in word endings.

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